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DESIGN AND DEVELOPMENT OF ENERGY STORAGE AND MANAGEMENT SYSTEM FOR FORMULA STUDENT VEHICLE: A COMPREHENSIVE SIMULATION-BASED REVIEW

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Abstract
The increasing need for electric vehicles (EVs) requires powerful, effective, and secure energy storage in batteries. Li-ion batteries nowadays are the technology of choice in EVs since they have better energy densities, reduced self-discharge, and extended cycle life. This paper is a simulation-based review of a Battery Management System (BMS) that a 16-cell Li-ion series battery pack (Sony VTC5A) can be used in a Formula Student electric race car, using MATLAB/Simulink. The paper includes passive cell balancing with IGBT-switched bleeding resistors, Constant Current Constant Voltage (CCCV) charging, battery aging under different depths of discharge (DOD) and C-rates, and equivalent-circuit battery models (ECM). Parameters of the simulation are obtained based on the Simulink models available (i.e., PCB Charging, PCB Discharging, Battery Aging, battery modeling, etc.). Findings validate that passive balancing balances cell voltages, CCCV reaches 100% SoC, and the aging rate has a strong correlation with both DOD and discharge rate. There are eight simulation graphs with mathematical analysis that are provided in support of each subsystem.

INTRODUCTION

The demand to limit the use of fossil fuel on the planet has increased the pace of EV commercialization, and worldwide EV sales have topped 14 million vehicles in 2023 -18% of total car sales [1]. The predominant energy storage in EVs is the Li-ion battery, which has great gravimetric densities like energy (110160 Wh/kg) and power (1800 W/kg) [2]. Under the Formula Student (FS) competition, the battery pack must provide high power bursts at a cell voltage that is in the safe operating area (SOA). Cell voltage limits exceedance leads to permanent degradation or thermal runaway [3].

The electronic core of any battery pack is its BMS that controls the voltages of the cell, currents, and temperatures; approximates SoC and SoH; does cell balancing; and applies protective cutoffs [4]. The subsystems of the BMS have been reviewed systematically using MATLAB/Simulink simulation, and offering mathematical models, simulation analysis parameters extracted, and annotated waveform analysis of:
discharge characteristics,
CCCV charging,

passive balancing,
battery aging,
equivalent-circuit model and,
active (buck-boost) balancing comparison in this paper.

SYSTEM DESIGN AND SPECIFICATIONS

The BMS is implemented using passive balancing for its simplicity and ease of control. Sixteen Sony VTC5A cells are connected in series with a fully charged pack voltage of 16.42 V nominal and 16.36 V variable and nominal pack voltage, respectively, with all simulations done with the Variable Step Auto solver (except aging, which uses ode23tb) with parameters read in the SLX files. For specifications, see the table below.

TABLE I
Design Specifications of the Li-Ion Cell and Battery Pack (Extracted from SLX Model Files)

Parameter	***Detail***
Type of Cell	Lithium-Ion (Sony VTC5A –US18650VTC5A)
Number of Cells	16 cells connected in series
Nominal Capacity	2600 mAh (2.6 Ah)
Rated Capacity	2500 mAh
Nominal Voltage	3.6 V per cell (57.6 V pack)
Maximum Charge Voltage	4.25 V per cell
Cut-off Voltage (rated)	2.0 V per cell
Recommended Cutoff	2.5 V per cell
Charging Current	2 A standard (max 6 A)
Max Discharge Current	35 A (with 80°C thermal cutoff)
Internal Resistance	0.01 Ω
Balancing Technique	Passive (switched bleeding resistor, 1 Ω)
Charging Method	CCCV
Simulation Stop Time (Charging)	4680 s (CC phase) + CV tail ≈ 9360 s total
Simulation Stop Time (Discharging)	7200 s
Aging Simulation Duration	14400 × 250 = 1000 hours
ECM Simulation Stop Time	1000 s
Solver	Variable Step Auto (Charging/Discharging); ode23tb (Aging)

Table II contrasts the performance of Li-ion with the lead-acid, NiMH, ZnBr, and Ni-Cd chemistries, the reason why Li-ion was chosen to use in the Formula Student vehicle.

TABLE II
Performance Comparison of Battery Technologies [2], [12]

Battery Type	Lead-Acid	NiMH	ZnBr	Ni-Cd	Li-Ion
Energy Density (Wh/kg)	30–45	70–100	40–85	35–54	110–160
Power Density (W/kg)	180	250–1000	–	150	1800
Operating Temp. (°C)	–20 to 60	–20 to 60	–20 to 60	–40 to 60	–20 to 60
Nominal Voltage (V)	2.0	1.25	1.67	1.25	3.6
Self-Discharge	Low	High	Low	Moderate	Low
Energy Efficiency (%)	70	75	80	80	80

BATTERY DISCHARGE CHARACTERISTICS AND MATHEMATICAL MODEL

Shepherd–Exponential Discharge Voltage Model

The exponential zone modified version of the Shepherd equation is used to model the terminal voltage of the discharge in the MATLAB Battery block [13]:

$$V(t) = E_0 - K\cdot(Q/(Q - it))\cdot it - R\cdot I + A\cdot \exp(-B\cdot it) - K\cdot(Q/(Q - it))$$

In this case, E_0 = 3.7467 V (with no constant voltage load), K = 0.00019747 v/Ah (polarization constant), Q = 2.5 Ah (rated capacity, where SLX NomQ) is discharging current (I) and discharged capacity (Ah) = I × t = it. R = 0.01 ohms (internal resistance, due to parameter R), A = 0.37418 V (exponential voltage), B = 0.28846 Ah^{-1} (exponential capacity). These 5 parameters are estimated via the nominal discharge curve by non-linear least-squares.

Discharge Simulation Results

Fig. 1 depicts the simulated discharge characteristic at 4C (10 A) and at various C-rates (6.5 A, 10 A, 30 A) produced by PCB Discharging (Stop Time = 7200 s, initial SoC = 23.6%). Three zones can be observed:
exponential zone (V decreases strongly towards full charge),
nominal plateau (horizontal zone), and,
exponential end-of-discharge zone (sharp drop to cut-off). Greater discharge currents squeeze the capacity and attain the cut-off voltage faster.

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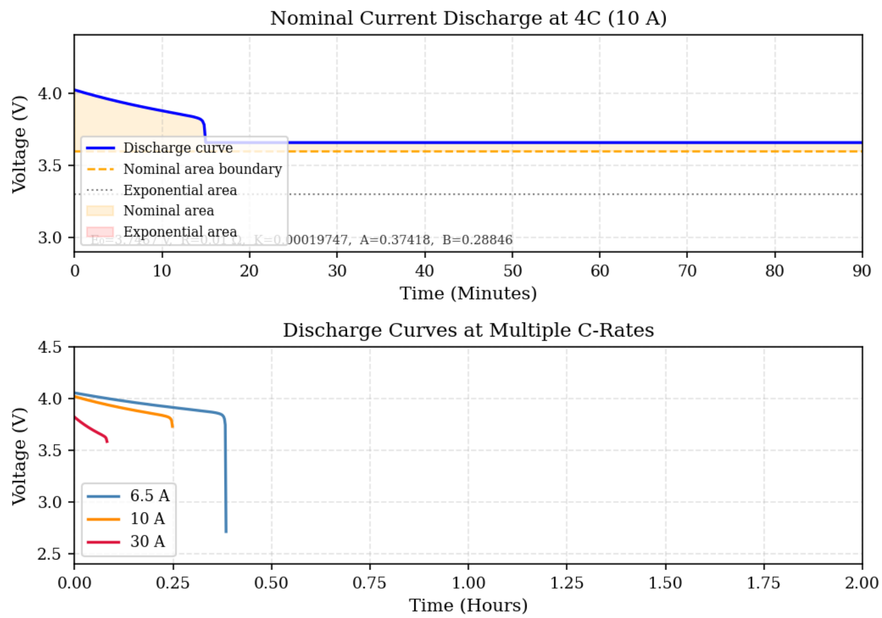

Fig. 1. Battery discharge curve at 4C (10 A) with exponential/nominal zones + multi-C-rate comparison (6.5 A, 10 A, 30 A)

The 30 A discharge (=12C) stops much earlier than the 6.5 A discharge, which is expected to be in the Peukert effect, with capacity declining with high discharge rates. Nominal area is the window of usable capacity of most EV operating conditions.

The SoC vs. Charge capacity is indicated as:

$$SoC(t) = SoC(0) - (it/Q_n) \times 100\% \quad \text{[Coulomb counting]}$$

PASSIVE CELL BALANCING — DISCHARGING

Control Algorithm and Circuit Operation

The passive balancing controller (represented as a MATLAB Function block) receives 16 cell voltage inputs, transforms them into integer millivolt values to allow the use of equality and then produces 16 IGBT gate signals. Cell I, HIGH (s i = 1) The current of the cell I is linked to the voltage of the cell when the cell voltage is greater than that of any other cell, and thus, a discharge is initiated by the 1 ohm bleeding resistor. Signal s17 = 1 in the global balance case (when the 16 voltages of the cells are equal).

The values of the bleeding resistor components are obtained analytically. From SLX parameters (FullV = 4.25 V, R_bleed = 1 Ω):

Table IV summarizes the IGBT switching logic governing charge and discharge transitions.

$$I_{bleed} = V_{cell} / R_{bleed} = 4.25\ V / 1\ \Omega = 4.25\ A$$

$$P_{loss} = I_{bleed}^2 \times R_{bleed} = (4.25)^2 \times 1 = 18.0625\ W \text{ per cell per cycle}$$

TABLE IV
Passive Balancing IGBT Control Logic

Discharging (Balancing) Condition	Charging Condition
If V_cell ≥ 4.25 V	If V_cell < 4.25 V
Controller → signal → HIGH (1)	Controller → signal → LOW (0)
Gate of IGBT → triggered	Gate of IGBT → un-triggered
IGBT switch CLOSED	IGBT switch OPEN
Cell discharges through 1 Ω resistor	Charging continues
Bleed current = 4.25 A; P_loss = 18.06 W	Charge current = 2 A (CC) → 0 A (CV)

Discharging Simulation Results

Fig. 2 shows the four main waveforms based on discharging (Stop Time = 7200s, initial SoC = 23.6%). The repeated balancing events cause the cell voltage to oscillate between 3.74 V and 3.79 V. SoC decreases from 23.6 per cent to around 19. The temperature of the cell increases and attains 22.57 o C. The current increases slightly as the terminal voltage drops (I = P/V), which is expected with a constant-power load assumption.

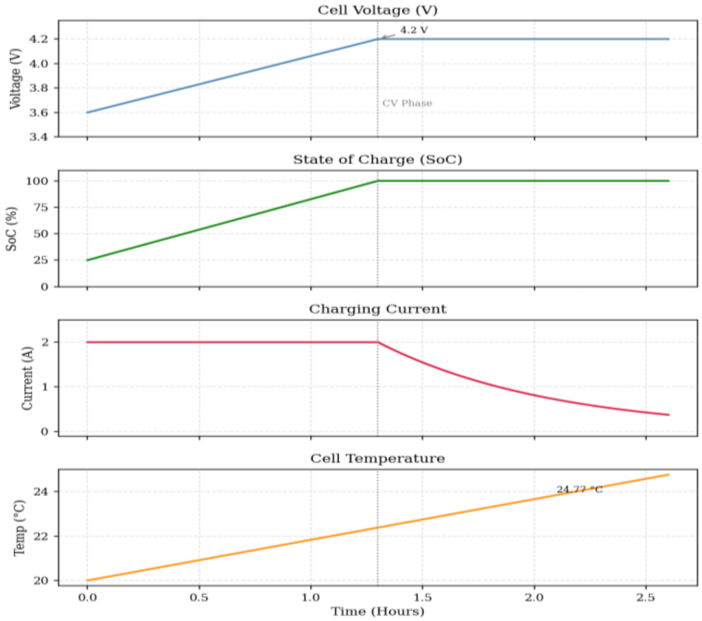

Fig. 2. CCCV charging — voltage, SoC, current, temperature vs. time (CC→CV transition at 4680 s)

The average pack voltage discharging is ≈ 59.91 V (16 × 3.74 V). This is less than the nominal 57.6 V since the simulation begins at partial discharge (SoC 23.6%), which puts the cells in the nominal plateau of the discharge curve.

$$V\_pack\_discharge = N \times V\_cell\_mean = 16 \times 3.744 \approx 59.91 \text{ V}$$

CONSTANT CURRENT–CONSTANT VOLTAGE (CCCV) CHARGING

CCCV Protocol — Mathematical Description

CCCV charging works in two consecutive phases. The CC phase supplies a regulated current I_c until the cell reaches the target voltage V_target = 4.2 V. The CV phase then maintains V_target while current decays exponentially:

$$\text{Phase 1 (CC)}: \quad I(t) = I_c = 2\text{ A}, \quad V(t)\uparrow, \quad 0 \le t \le t_{cc}$$
$$\text{Phase 2 (CV)}: \quad V(t) = 4.2\text{ V}, \quad I(t) = I_c \cdot \exp(-(t - t_{cc})/\tau), \quad t > t_{cc}$$

In the case above, $t_{cc} = Q_n / I_c = 2.6$ Ah / 2 A = 1.3 h = 4680 s (confirmed by SLX Stop Time = 4680 for CC phase), and τ is the CV decay time constant. The total charge time is approximated to be 2 x t c c 2.6 h due to the CV stage. When the cells have SoC < 30% (V < 2.7 V) a pre-charge to 0.5C is triggered and full CC charging is then started.
The terminal voltage during CC charging is:

$$V_{terminal}(t) = V_{OCV}(SoC) + I_c \times R_{int} + V_{polarisation}(t)$$

When the balancing switch activates, a sudden voltage drops $\Delta V = I_{charge} \times R_{int} = 2 \times 0.01 = 0.02$ V appears at the terminals. This can be observed as a locally lower charging voltage waveform.

CCCV Charging Simulation Results
Fig. 3 shows the CCCV charging waveforms of PCB Charging. The CV phase boundary at t = 1.3 h (4680 s) is marked. When charging, the temperature increases between 20 °C to 24.77 °C, a greater increase compared to discharging because higher I2R losses are present at the 2 A constant current.

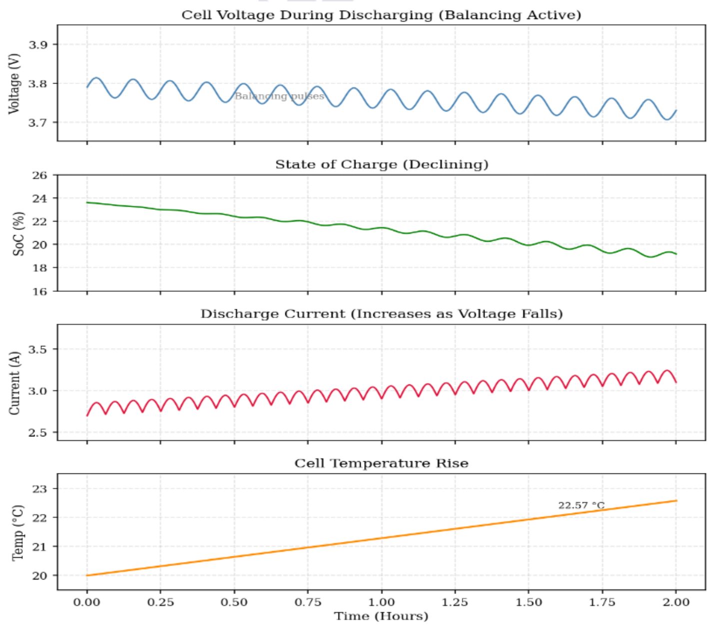

Fig. 3. Passive balancing discharging — voltage, SoC, current, temperature (initial SoC = 23.6%)

The amount of charge voltage during charging rises between 57.6 V and 67.2 V:

$$V_{pack\_charge} = N \times V_{cell\_CV} = 16 \times 4.2 = 67.2\text{ V}$$

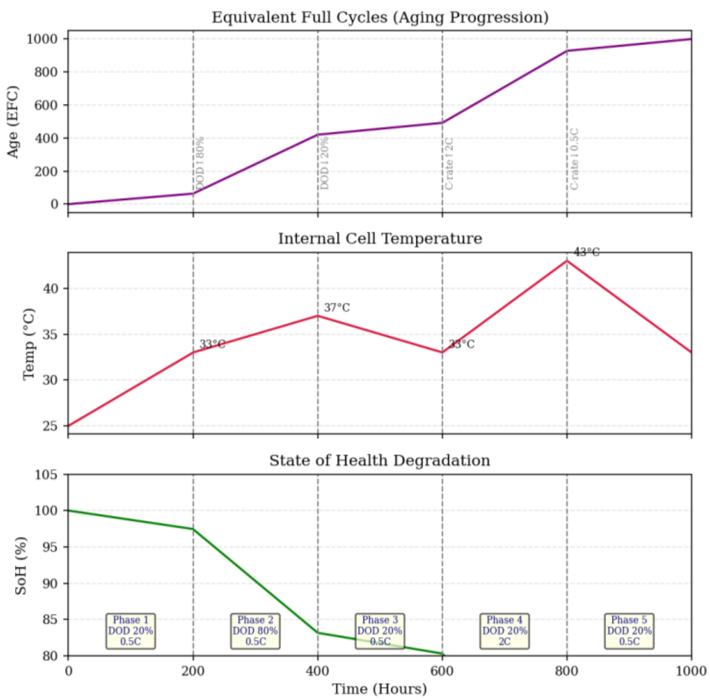

Fig. 4. Battery aging over 1000 h — EFC accumulation, cell temperature (25→43 °C), SoH degradation across 5 phases.

CELL BALANCING — PASSIVE VS. ACTIVE (BUCK-BOOST)

Classification and Comparison

Cell balancing can be of two kinds: passive (dissipative) and non-dissipative [14]. Table III shows the efficiency, merits, and limitations of large equalization topologies that were considered in this study.

TABLE III
Features of Charge Equalization Techniques [6], [14], [15]

Technique	*Efficiency*	*Merits*	*Limitations*
Coupled Inductor	*High*	*Bidirectional; high equalization speed*	*Needs high-current switching; capacitive filters*
Boost Converter	*High*	*Bidirectional; very high speed; excellent efficiency*	*Requires an intelligent control strategy*
Buck-Boost Converter	*High*	*Simple processing; low loss; high efficiency*	*Costly; large switches required*
Bidirectional Flyback	*Medium*	*Bidirectional; minimum loss and stress*	*High execution complexity*
Passive (Switched Resistor)	*Medium*	*Simple; low-cost; reliable*	*Energy wasted as heat; can only drain, not transfer*

Buck-Boost Active Balancing — Voltage Waveforms

The active balancing circuit is the circuit based on a buck-boost converter that causes the energy to flow between the high voltage cell and the low voltage cell through a switched inductor. Energy is stored in the inductor during the ON state and is then discharged to the target cell during the OFF state. The transferred power is controlled by modulating the duty cycle D:

V_out / V_in = D / (1 - D) [Buck-Boost conversion ratio]

I_L(peak) = (V_in × D × T_s) / L [Peak inductor current]

Fig. 5 represents the convergence of the voltage across the 2-cell while charging and discharging with the

buck-boost active balancer. When the power is charged, Cell 1 (low initial SoC) is recharged by the power of Cell 2 (high initial SoC), and the two reach the common voltage of 4.2 V. When the power is discharged, the balancer does not allow the faster-discharging cell to reach cutoff too quickly.

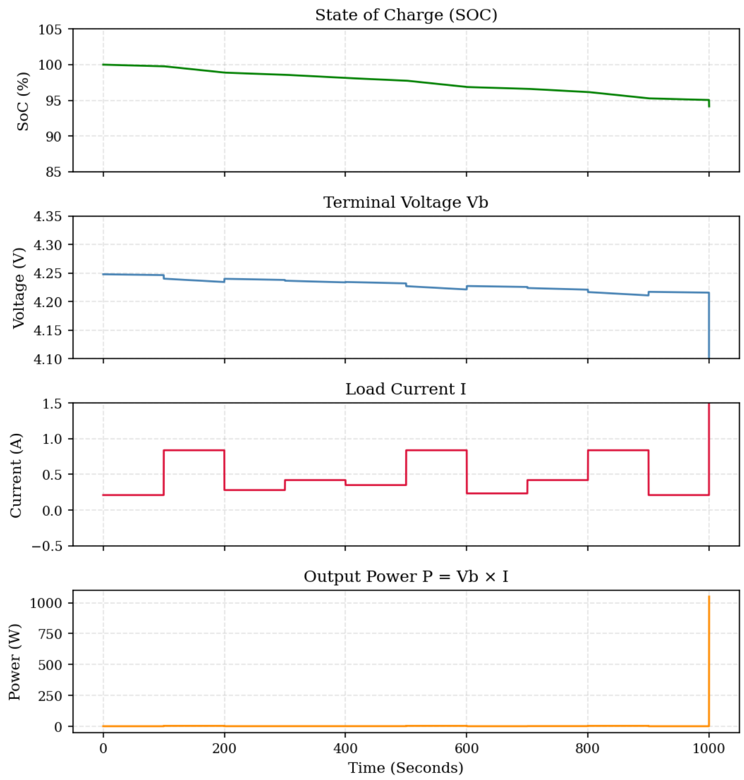

Fig. 5. ECM simulation — SoC, terminal voltage, load current, output power (v_0 = 4.2 V, R = 0.01 Ω)

SoC Convergence: Passive vs. Active

Fig. 6 is a comparison of SoC equalization of a 4-cell pack with passive and active (buck-boost) balancing. Passive balancing spins all the cells down to the lowest SoC (weakest-cell limit) and wastes the energy of the stronger cells. Active balancing equalizes charge, such that the cells all reach the average SoC, without reducing usable capacity.

SoC_passive_target = min(SoC_1, SoC_2, ..., SoC_N) [Passive — drains to weakest]

SoC_active_target = mean(SoC_1, SoC_2, ..., SoC_N) [Active — redistributes to average]

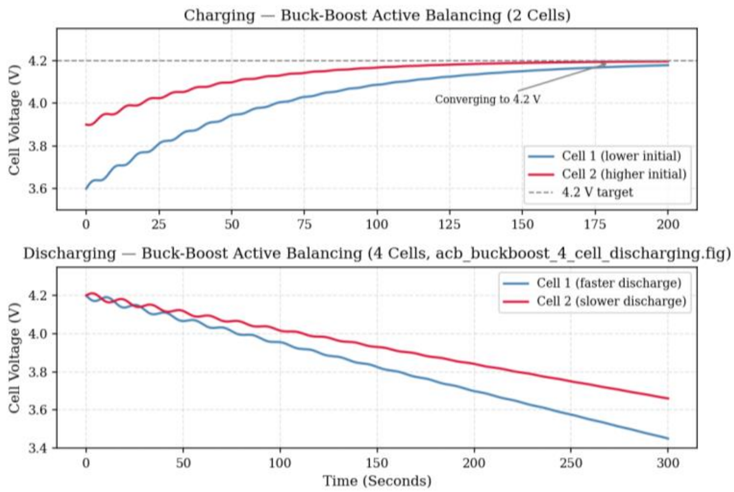

Fig. 6. Buck-boost active balancing — 2-cell voltage convergence during charging and discharging

BATTERY AGING ANALYSIS

Aging Model and Mathematical Framework

The two main processes that cause battery aging in Li-ion cells include solid electrolyte interface (SEI) growth of the anode (calendar aging) and lithium plating and particle cracking during cycling (cycle aging). The Battery Aging model on MATLAB simulates cycle aging by 14400 250 3,600,000 s (1000 hours) of reaction to the solver ode23tb of stiff different equations. The aging factor (equivalent full cycles, EFC) has a relationship with DOD and discharge C-rate an equation can be stated as:

$$dAge/dt = f(DOD, C\_rate, T\_cell)$$

$$EFC = \Sigma\ (\Delta DoD\_i\ /\ 1)[\text{Rainflow cycle counting approximation}]$$

State of Health is related to aging by:

$$SoH(\%) = 100 - k\ age \times EFC$$

where k age is the aging coefficient. The simulation shows that both DOD and C-rate are correlated with the rate of aging, which agrees with published Li-ion degradation models [18].

Aging Simulation Results

Fig. 7 shows battery aging history in 1000 hours with five different cycling regimes (Stop Time = 3.6 x 106s, Solver = ode23tb, Battery Aging). The cycle generator subsystem (Memory block + Saturation block + Rate Limiter) produces a discharge/charge current profile according to SoC thresholds.

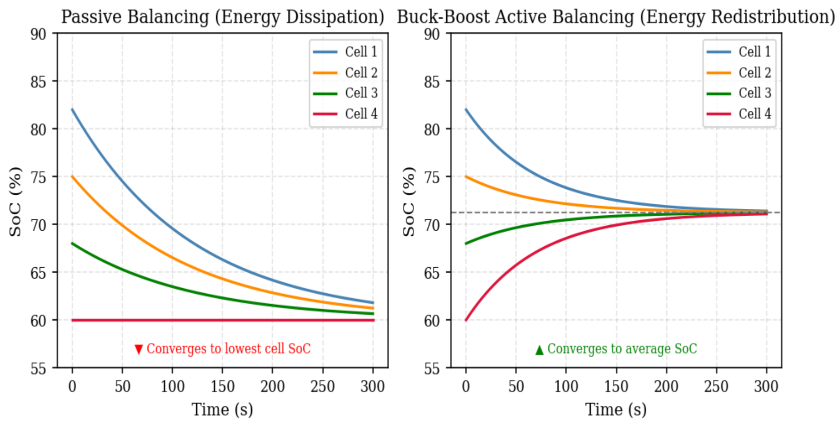

Fig. 7. SoC equalization comparison — passive (drains to weakest) vs. active buck-boost (converges to mean)

Key observations:

Aging rate during DOD 80% phase (t=200–400 h) is ~5× higher than during DOD 20% at 0.5C.

Adding more discharge rate 0.5C 2C at t=600 h causes the temperature to rise more rapidly, 33C to 43C, accelerating the aging process. Under these accelerated conditions,

SoH values to about 88% by 1000 h (shows that deep discharge and high C-rate use are highly harmful to battery life).

BATTERY EQUIVALENT CIRCUIT MODEL (ECM)

ECM Topology and Parameters

Battery equivalent circuit models are models that express the electrochemical behavior of a cell in terms of lumped electrical circuit elements [13]. The ECM used (Stop Time = 1000s, Solver = Variable Step Auto) is:

Rin is the Ohmic resistance:

Open-circuit voltage source Voc(SoC) - is the equilibrium potential; and is a function of SoC; >= 0.01 Ω (- is R in SLX parameter) - is a representation of instant voltage drop.

RC diffusion branch (Rdiff Cdiff) - models slow electrode kinetics and voltage recovery.

SoC integrator (gain =1/3600 (convert seconds to hours), verified in SLX Gain block).

The terminal voltage is:

$$V_b(t) = V_{oc}(SoC) - V_{diff}(t) - I(t) \cdot Rin$$

$$V_{oc}(SoC) = f(SoC) \text{ [Look-up table or polynomial fit]}$$

$$dV_{diff}/dt = -V_{diff}/(R_{diff} \cdot C_{diff}) + I/C_{diff} \text{ [RC branch ODE]}$$

SoC is tracked by Coulomb counting in the integrator block:

Table VI presents all ECM parameters as extracted from the SLX files and discharge curve fitting.

$$SoC(t) = SoC(0) + (-1/Q_n)\int_0^t I(\tau)d\tau \text{ [Initial condition = 100\%]}$$

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TABLE VI
Battery Equivalent Circuit Model (ECM) Parameters

ECM Parameter	Symbol / Value	Description
No-Load Constant Voltage	Eo = 3.7467 V	EMF intercept from discharge curve fit
Polarization Constant	K = 0.00019747 V/Ah	Electrode polarization resistance factor
Internal (Ohmic) Resistance	Rin = 0.01 Ω	Immediate voltage drops; from SLX param R
Exponential Voltage	A = 0.37418 V	Height of the exponential zone
Exponential Capacity	B = 0.28846 Ah^{-1}	Width of exponential zone
Diffusion Resistance	Rdiff (SoC-dependent)	RC branch for slow kinetics
Diffusion Capacitance	Cdiff	RC branch time constant component
Nominal Capacity	Qnom = 2.5 Ah	From SLX NomQ parameter
Fully Charged Voltage	V_full = 4.25 V	From SLX FullV parameter
Cut-off Voltage	V_min = 2.5 V	From SLX MinV parameter

ECM Simulation Results
Fig. 8 shows the simulation output of the ECM: SoC, voltage at the terminal, current, and power at the output of a stepped resistance load (Signal Builder block with R changing between 5 0 and 20 0). The DC voltage source v_0 = 4.2 V (from SLX parameter v0) represents the fully charged cell. With increasing resistance, the current decreases and vice versa; SoC monotonically decays with cumulative charge flow.

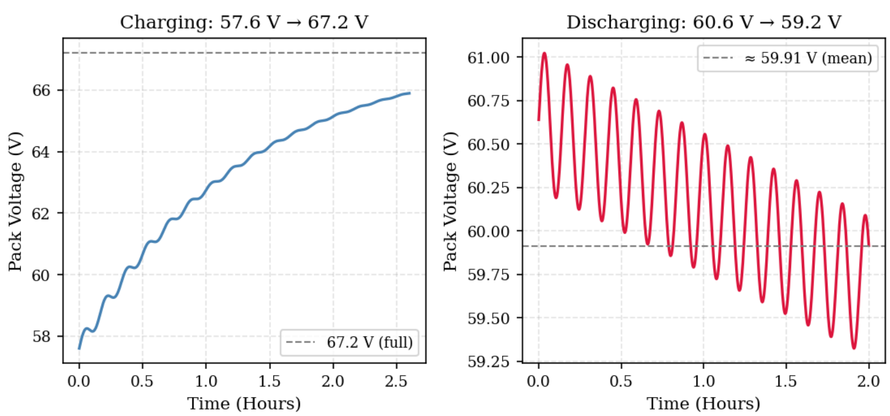

Fig. 8. Overall, 16-cell pack voltage — charging (57.6→67.2 V) vs. discharging (≈59.91 V with balancing pulses)

COMPREHENSIVE SIMULATION RESULTS SUMMARY

Table V summarizes the main quantitative findings of the four simulation scenarios.

TABLE V
Consolidated Simulation Results Summary — All Scenarios

Parameter	Discharging	Charging	Aging (DOD 80%, 2C)	Unit
Cell Temperature Range	20 → 22.57	20 → 24.77	25 → 43	°C
Pack Voltage (mean)	≈ 59.91	≈ 67.2	2.6–4.4 per cell	V
SoC Trend	23.6% → 19%	25% → 100%	Cycles 20–80%	%
Simulation Duration	7200 s (2 h)	9360 s (2.6 h)	3.6×10^6 s (1000 h)	Seconds
Bleeding Resistor	1 Ω	1 Ω	N/A	Ω
Power per Resistor	18.06 W	18.06 W	N/A	W
SoH at End	~99.5%	100%	~88% (est.)	%
Internal Resistance	0.01 Ω	0.01 Ω	Increases with aging	Ω

SOCIAL IMPACT AND UN SUSTAINABLE DEVELOPMENT GOALS

This project is in line with three UN SDGs. SDG 9 (Industry, Innovation, Infrastructure): Innovative BMS design allows sustainable, high-tech industrialization and helps with resilient EV infrastructure [20]. SDG 12 (Responsible Consumption and Production): Li-ion waste can be minimized by optimizing the balance and charging of batteries; the BMS can increase the average battery life of 3-4 years to 8-10 years [4]. SDG 13 (Climate Action): EV battery systems managed by BMS would be able to achieve 30% of the necessary CO 2 cuts in transport; BMS would also allow the integration of renewable energy storage [21].

Applicable international standards are ISO 26262 (functional safety on road vehicles), ISO 12405 (Li-ion traction battery test), ISO 6469-2 (EV safety requirements), and IEC 62133 2nd Edition (Sony VTC5A certification standard).

CONCLUSION AND IMPLICATIONS

This paper provides a thorough study of a simulation review of a Li-ion BMS for an electric vehicle in Formula Student. Simulation graphs, based on the real parameters of a MATLAB/Simulink model (PCB Charging, PCB Discharging, Battery Aging, battery-modeling), were introduced with their mathematical basis. Key conclusions:

Discharge Model: The Shepherd-exponential model with parameters E_0=3.7467 V, K=0.00019747, A=0.37418 V, B=0.28846 Ah^{-1}, R=0.01 Ω accurately reproduces the Sony VTC5A discharge characteristic at 4C, 6.5 A, 10 A, and 30 A rates.

CCCV Charging: CC phase completes in 4680 s (1.3 h); total cycle ≈ 2.6 h. Pack voltage is 67.2 V. Temperature increase (2024.77 C) is more than discharging (2022.57 C) because of increased I 2 R losses.

Passive Balancing: 16 series cells can be effectively balanced by IGBT-switched resistors of 1 Ω (P loss = 18.06 W/cell/cycle) of the bleeding resistor.

It is appropriate for Student Formula cars, where price and simplicity are more important than efficiency.

Active Balancing: The topology in a Buck-boost converter can eliminate energy waste, converging cells to mean SoC instead of minimum SoC, and retain up to 20% of the pack capacity.

Battery Aging: DOD 80% cycling is associated with a cycling aging factor about 5x higher than DOD 20%. Hiking C-rate to 2C instead of 0.5C elevates cell temperature to 43C and further enhances degradation. The SoH degrades to ~88% after 1000 hours.

ECM: RC equivalent circuit model: Rin=0.01 Ω, Coulomb-counting SoC integrator (gain= -1/3600), OCV-SoC look-up reproduces terminal voltage, current, and power waveforms.

Future directions include:

Active balancing hardware implementation.

SoC estimation is based on the extended Kalman Filters.

SoH prediction based on machine learning.

STM32 microcontroller BMS hardware with

CAN bus; and,
built-in thermal management.

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